Dynamical Studies in Hurricane Intensity Change

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LONG-TERM GOALS AND OBJECTIVES

The long-term goals and objectives of this research are to develop a physical understanding of tropical cyclone (TC) intensity change processes. Towards this goal, this year's work focused on two main areas: asymmetric dynamics of the TC inner-core region and completion of our intensification study of Hurricane Opal (1995). These projects are complementary and represent important advances in our understanding of intensity change mechanisms. The following pages summarize our findings.

- **Simulation And Analysis Of Vorticity Mixing In Baroclinic, Hurricane-Like Vortices:**

APPROACH

Evidence for complex, asymmetric inner-core dynamics in tropical cyclones has been observed for some time, such as the appearance of polygonal eyewalls in satellite and radar observations, and also in-situ observations of mesovortices within the eye. Inner-core asymmetric processes have recently been implicated as essential for rapid hurricane intensification (Emanuel, 1997). In the previous year, we initiated a more thorough study of these phenomena by considering the asymmetric dynamics and stability of fully three-dimensional disturbances in a three-dimensional, hurricane-like vortex. Considerable progress has been made on both research fronts.

WORK COMPLETED, RESULTS, IMPACT, AND APPLICATIONS

We are studying the dynamics of inner-core asymmetries with two complementary methods. The first involves directly simulating such asymmetries with a high-resolution non-hydrostatic mesoscale numerical model (RAMS). Working with Lewis Grasso of CIRA, we have simulated the emergence, growth, and nonlinear equilibration of asymmetries in the core of an idealized, initially balanced, hurricane-like vortex. The second approach involves a classical stability analysis of such vortices. This work extends previous work by allowing for a truly three-dimensional, baroclinic vortex, with substantial variations of the wind and temperature fields in the vertical direction. The formulation is constructed so that, like the basic-state, the associated eigenfunctions can vary arbitrarily in both the vertical and radial directions, retaining harmonic variations only in the azimuthal direction. From this analysis we have found that hurricane-like vortices are indeed unstable to low wavenumber perturbations that appear in the eyewall region, in remarkable agreement with previous two-dimensional studies (e.g., Weber and Smith, 1993; Schubert et al., 1999). The unstable modes are

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14. ABSTRACT
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approximately barotropic in nature and act to warm and spin up the eye. The unstable eigenmodes modes show good agreement with the early evolution of asymmetries in the RAMS model (see Figure 1). Preliminary results were presented at the recent AMS Hurricanes conference (Nolan and Montgomery, 2000c).

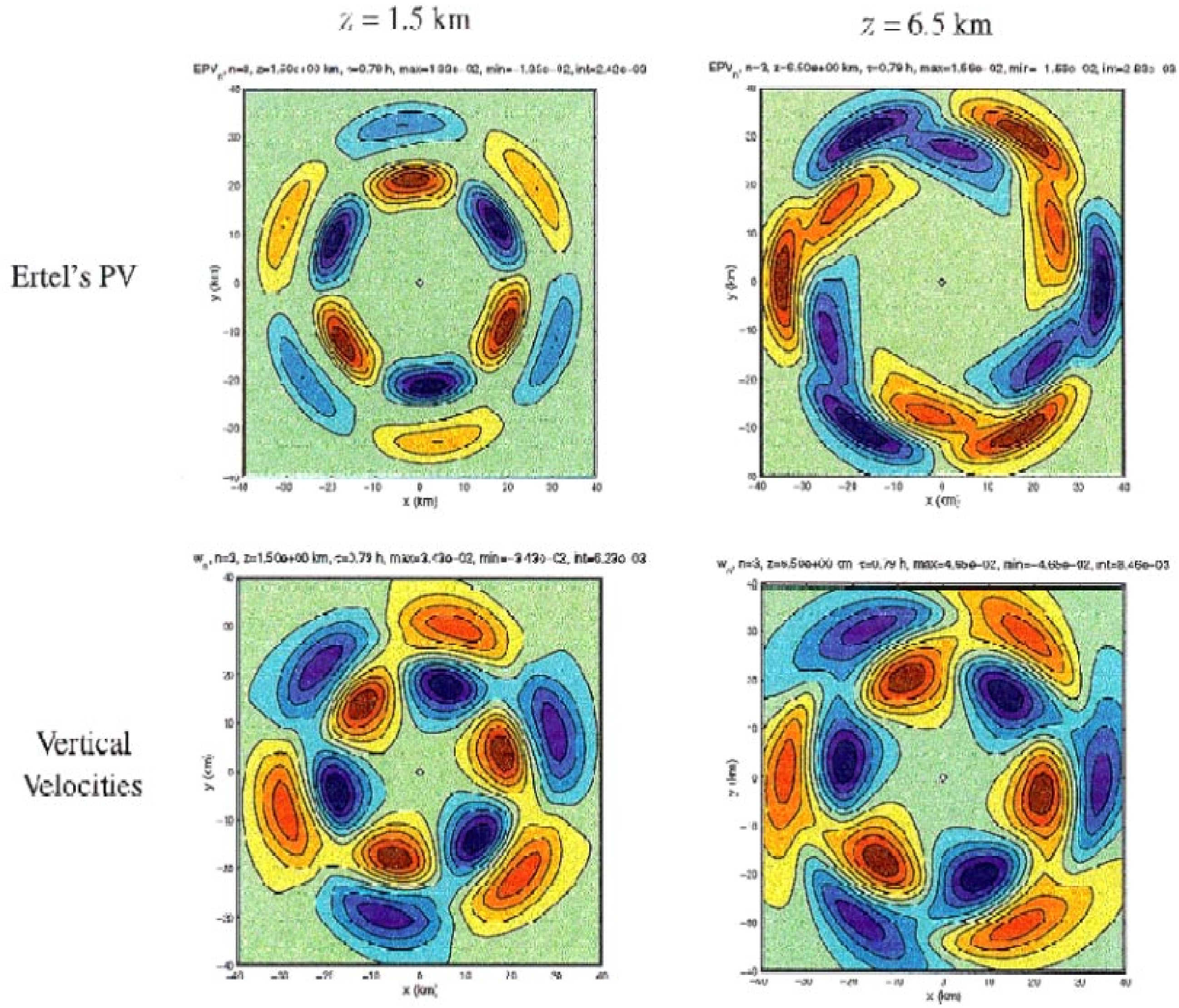

Figure 1: The structure of the most unstable mode in the core of a dry, balanced, category 3 hurricane-like vortex, in terms of its associated potential vorticity and vertical velocities. The e-folding time of the mode is 0.79 hours.

FUTURE WORK

While the wind and temperature fields of the basic-state are closely modeled after actual hurricanes, the vortex used here is without a secondary circulation. A natural next step in our stability analysis is to include the secondary circulation in the basic-state, so as to determine the effects of the radial inflow at low levels and vertical motion in the eyewall region on the stability of the vortex. Such an analysis is a nontrivial extension of similar published work on highly idealized vortices (Nolan and Farrell, 1999). The source for the basic state for such studies will be provided by the results of an axisymmetric hurricane model, such that the wind and mass fields are in dynamical balance with the secondary circulation. This basic research is essential in order to correctly diagnose the inner-core vorticity dynamics and thermodynamics currently being simulated by full-physics mesoscale models. It is our position that accurate hurricane intensity forecasts will not be achieved until these inner-core processes are understood.

- **Hurricane Intensification Resolved By A Hydrostatic Primitive Equation Model:**

APPROACH

Hurricane Opal (1995) crossed the Gulf of Mexico rapidly intensifying to a 130 kt storm, and then fortunately weakened before landfall on the Florida panhandle. This intensification was underforecast by the National Hurricane Center. Forecast fields from the 1997 version of the Geophysical Fluid Dynamics Laboratory Hurricane Prediction System (GFDL model) for Hurricane Opal were used to diagnose the rapid intensification of the tropical cyclone. While falling short of the realized peak intensity, the simulation did capture the phase of intensification. This presented a unique opportunity to diagnose the mechanisms for intensification within a moderate resolution (~ 15 km) hydrostatic model and test the extant hypotheses in the literature.

WORK COMPLETED, RESULTS, IMPACT, AND APPLICATIONS

Using a mean tangential momentum budget, positive eddy vorticity fluxes aloft were identified in the vicinity (~ 600 km) of Opal, but this signature was as apparent during the intensifying stage as in the subsequent weakening stage of the storm. A detailed examination of each of the terms in the budget (mean and eddy vorticity flux, mean and eddy vertical advection, and "friction") showed that for the most rapidly intensifying episodes the forcing for mean tangential wind near the center of the storm was dominated by the mean vertical advection and mean vorticity flux terms. Upper-level divergence exhibited significant vertical structure, such that single-level or layer-average analysis techniques did not capture the divergence signature aloft. Far from the storm (farther than 400 km), divergence features near 200mb were significantly influenced by convective events over land that were, perhaps, only indirectly influenced by the hurricane. The environmental vorticity distribution was examined and it was found that the interaction with a trough to the northwest extended down to 500mb. Upscale transfer of energy from the mesoscale to the synoptic scale by the hurricane circulation was shown to distort the synoptic scale flow. Based on this analysis, our conclusion is that the hurricane intensified without a beneficial interaction with specific features of the atmospheric environment. This conclusion is based on our finding of small positive eddy signals in the budget analysis during the intensification phase. Thus Opal developed, for the most part, in a manner to realize its maximum potential intensity. Imposed shear is proposed to weaken the storm at later times of the simulation (before landfall), and the signature of this weakening was also illustrated with the tangential momentum budget.
The diagnostic tools developed for this study can be readily applied to other cases simulated by the GFDL hurricane model or other mesoscale numerical models, such as RAMS or MM5.

TRANSITIONS

During FY2001, we plan to continue our study of inner-core vorticity mixing using the RAMS model, which will shed new light and understanding on the basic physics of hurricane intensity change. In addition, we plan to develop an algorithm for synthetically adding or removing PV anomalies in the GFDL hurricane model and in RAMS or MM5. This will allow more rigorous testing of whether observed PV anomalies in the hurricane environment contribute to strengthening or weakening the simulated storm.

RELATED PROJECTS

Dominique Möller (University of Munich) and MTM have completed their theoretical study of the dynamics of continuously stratified three-dimensional vortex Rossby waves in hurricane-like vortices using the three-dimensional Asymmetric Balance (AB) developed during her appointment as a post-doc at CSU.

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